Part 2: OVERLAND FLOW MODELING THRU THE CITY OF JOLIET, ILLINOIS USING HEC-RAS 2D

Illinois State Water Survey

Champaign-Urbana, Illinois

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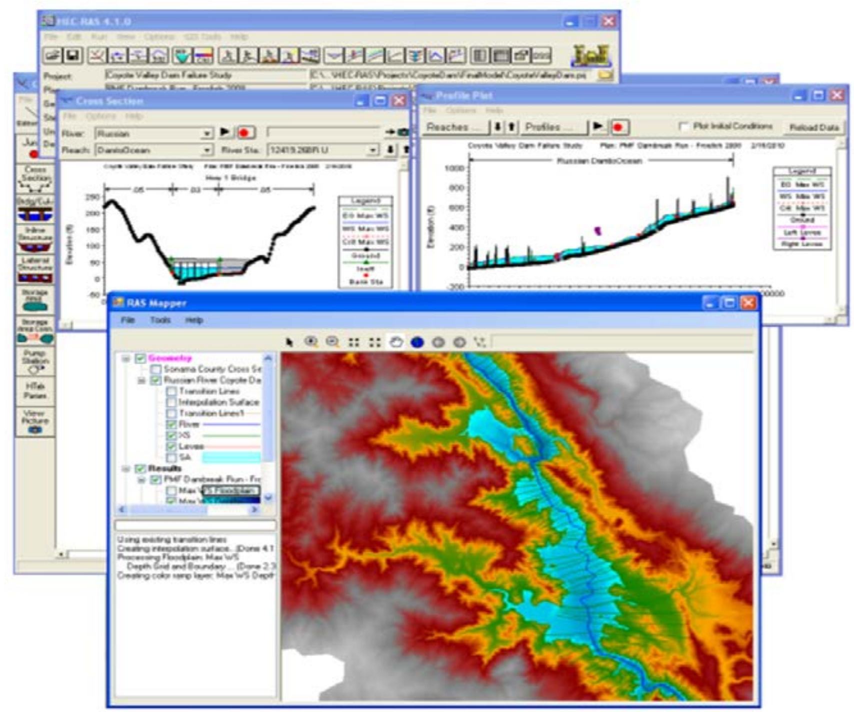
September 7, 2017

ILLINOIS STATE WATER SURVEY
PRAIRIE RESEARCH INSTITUTE

Outline

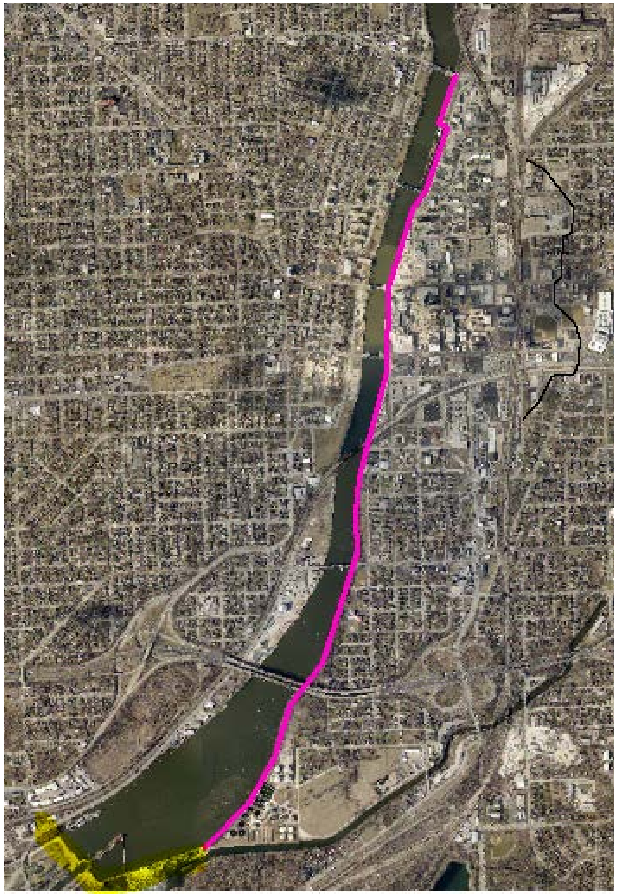
- Discovery of the City's Vulnerability
- Risk Analysis by STARR (Part 1)
- Risk Analysis by ISWS (Part 2)
  - 2-D Flow Area
  - Why we used a 2-D Model?
  - Closer look at 2-D Modeling
  - Discussion of Results
  - Summary



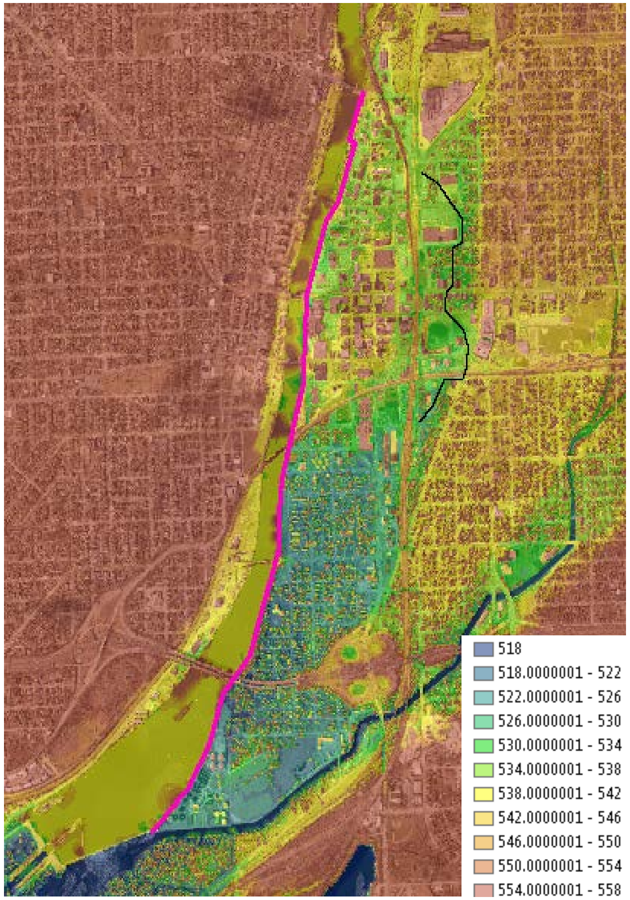
HEC-RAS River Analysis System, 2D Modeling User's Manual, Version 5.0, April 2015

Project Overview

1. The City of Joliet is bisected by the Des Plaines River.
2. The west side is on a bluff, east is low-lying and is protected by the floodwall.



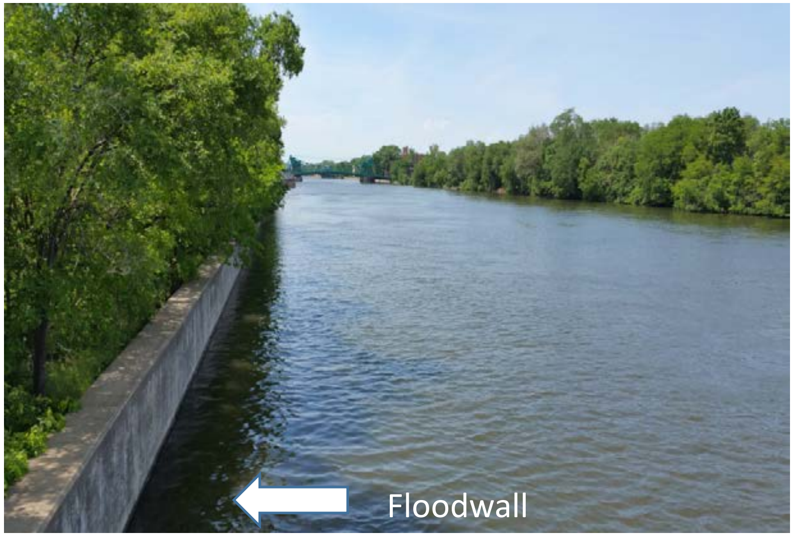
Des Plaines River Thru Joliet



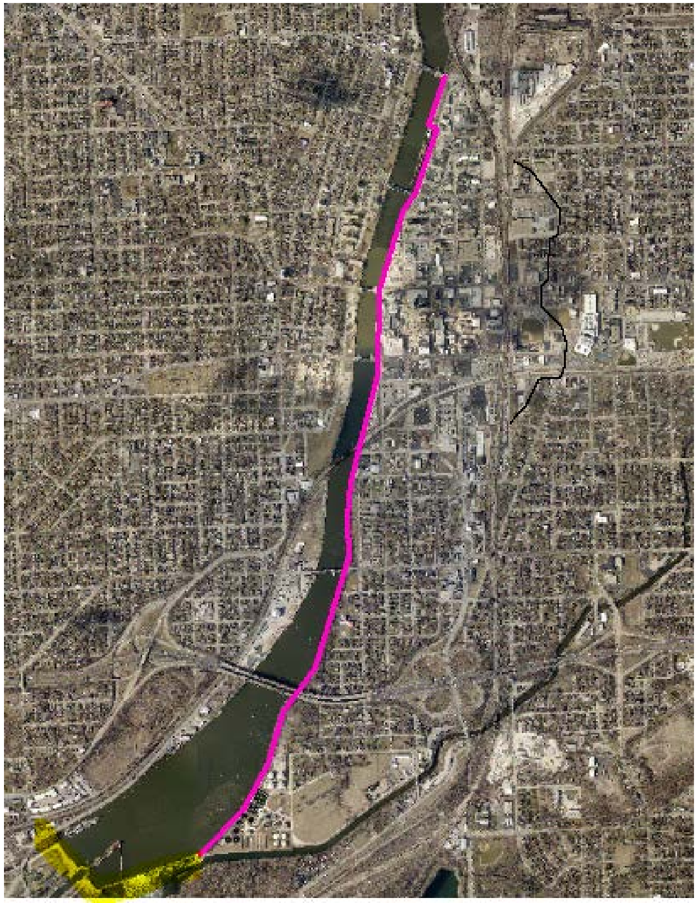
2014 LiDAR-derived DSM

Project Overview – cont'd

1. The east side is mapped on the effective FEMA FIRM as being protected from the 1% annual-chance flood by a floodwall along the Des Plaines River. It's part of the Brandon Road Lock & Dam system and run by the COE. The system provides a navigation pool.



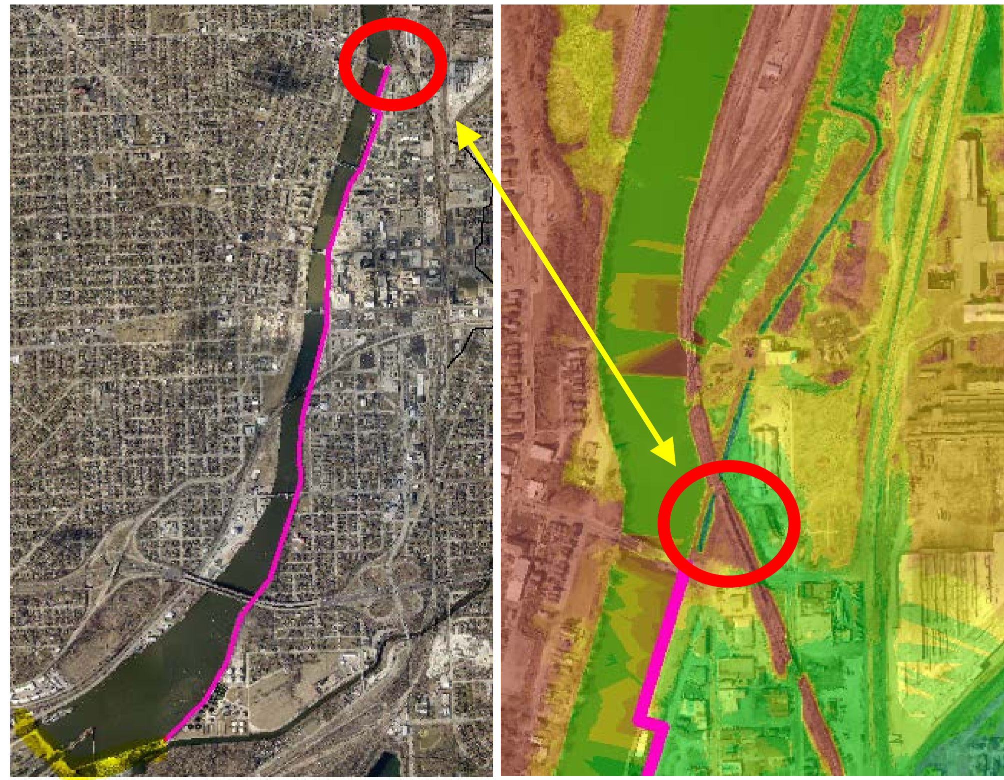
Looking downstream from Ruby Street Bridge: Floodwall Along the Eastern Shore of Des Plaines River



2.5-mile long floodwall. Brandon Road Lock & Dam.

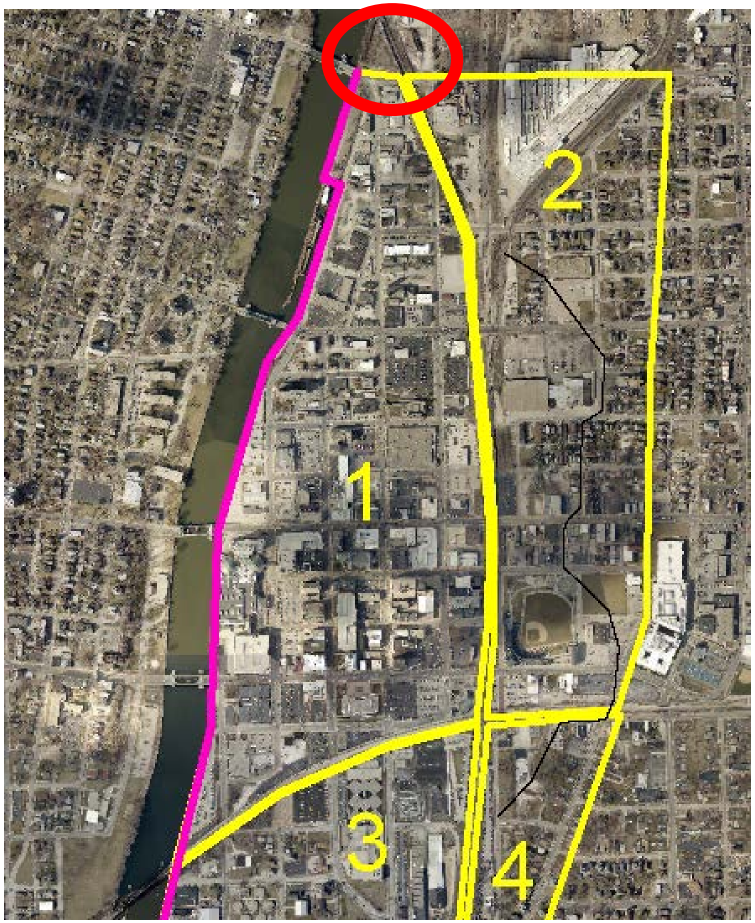
Project Overview – cont'd

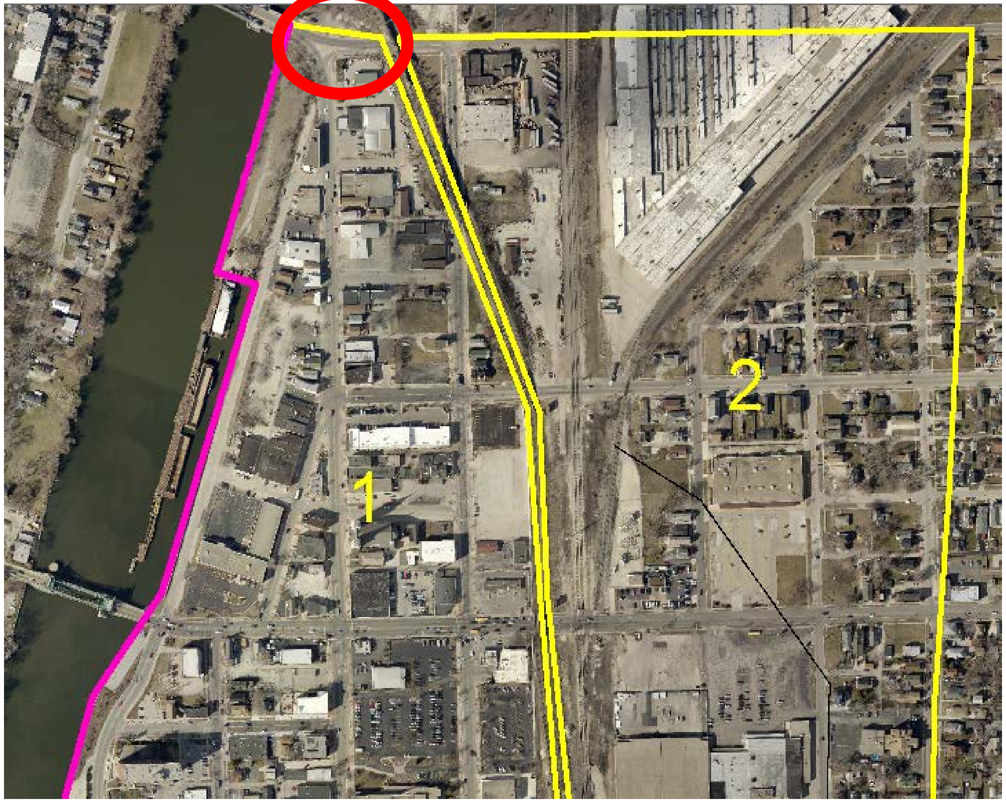
1. Upstream of the floodwall, Part 1 (STARR) of this project studied a scenario where flow from the Des Plaines River could enter the north side of the City of Joliet thru an embankment.
2. A 2D HEC-RAS model was developed by the ISWS to study how this flow would travel thru the numerous overland flow paths thru the City.



Floodwall

2-D Flow Area





Risk Analysis by STARR

STARR’s Hydraulic Routing Report

- The City has a good stormwater system but they decided that their system did not have the capacity to handle this large flow.

- This area hasn’t flooded from a rainfall event because of the stormwater system. They have had flooding in other parts of the City along Hickory and Spring Creeks, but not in this area. Remember though, this is not a direct rainfall event occurring within the small watershed of the City, it’s flooding from a scenario where flow from the Des Plaines (1,500 square mile drainage area) moves across a non-levee embankment.

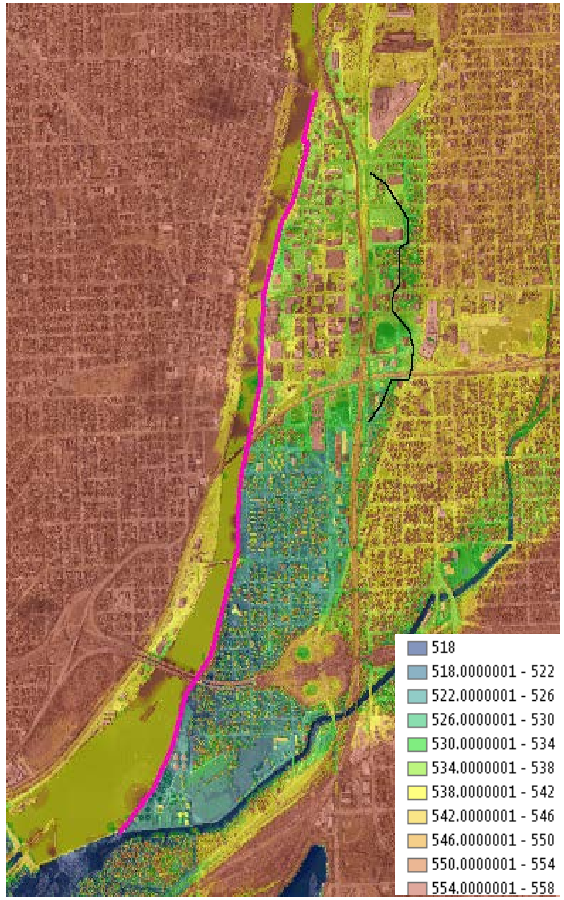
Risk Analysis by ISWS

Risk Analysis by ISWS

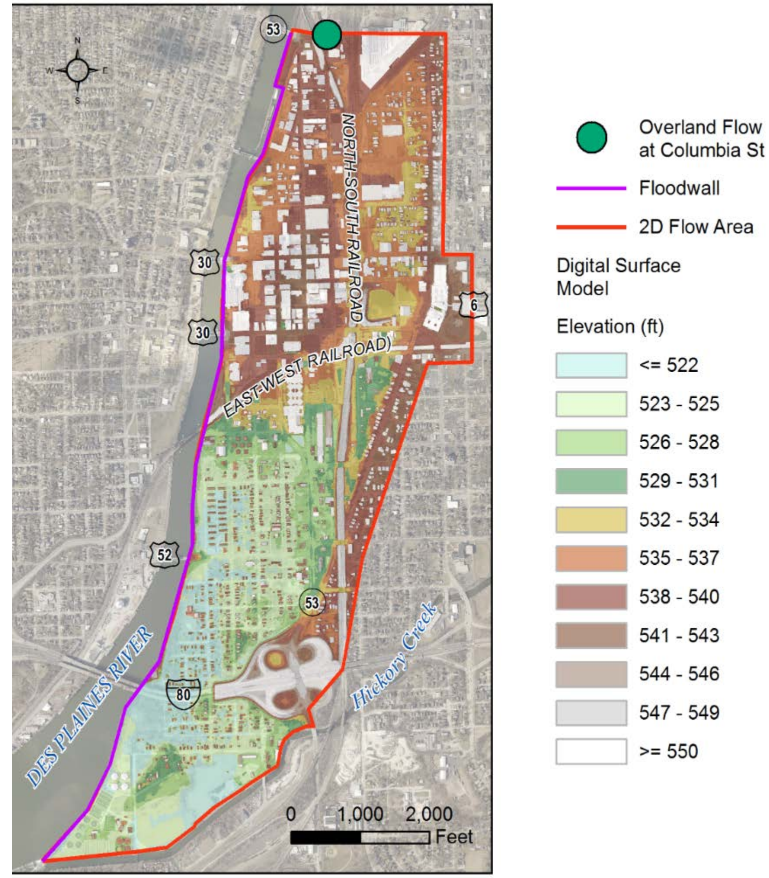
1. FEMA tasked the ISWS to model the flow thru the City.
2. Main purpose of this study is to communicate flood risk to the City.
3. After analyzing the study area, we determined that a steady-state 1-D hydraulic model would not accurately capture the overland paths thru the City and a 2-D model was used.

2-D Flow Area

1. The City of Joliet is bisected by the Des Plaines River.
2. The west side is on a bluff, east is low-lying.
3. 2D Flow Area:
   - Approximately 2.5 miles long; ½ mile wide.
   - Slopes to the south;
   - Approx. 30 feet of relief north to south
   - Bounded on west by floodwall and Eastern Ave on East side.
   - Overland flow enters at Columbia St and exits into Hickory Creek.
   - Area is compartmentalized by north-south and east-west RR embankments. DSM was hydrologically corrected to consider cross-street openings.
   - Numerous business & residential structures.



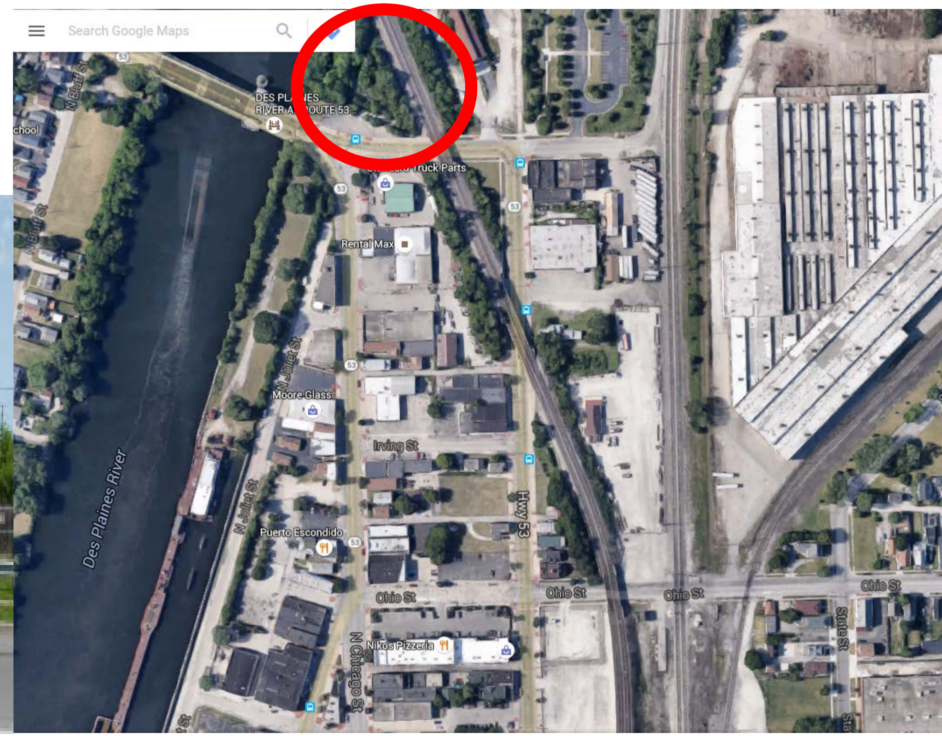
2014 LiDAR-derived DSM



2-D Flow Area Thru Joliet

2-D Flow Area– cont'd

Looking north of Ruby/Columbia Street and upstream where overland flow enters the 2D Flow Area to the right of RR Bridge.



2-D Flow Area– cont'd

Looking east: Example of a Cross Street opening through the North-South Railroad Embankment

2-D Flow Area– cont'd

Outlet of Study Area

Hickory Creek at the southern boundary of study area (looking down stream).

Why we used HEC-RAS 2-D

Why a 2D Model?

- The urban conditions have numerous flow paths thru streets and around buildings, which cannot easily be accounted for with 1-D model.
- A 1-D model considers velocity in longitudinal (downstream) direction based on strategic placement of cross sections (i.e., water goes only where you tell it to thru the placement of cross sections and in reality water may not go where the cross sections are).
- A 2-D model considers both longitudinal and lateral flow velocity
  - Cross sections were used for this study only at the boundary conditions; instead the physical landscape was captured by a gridded terrain model based on LiDAR. Very important to have accurate topographic data!
  - Other models may be comprised of both 1-D and 2-D components: 1-D for channel and 2-D for floodplains and overland flow areas.
  - Has the capability to determine flow paths around buildings and other structures through the 2D Flow Area.

What is HEC-RAS?

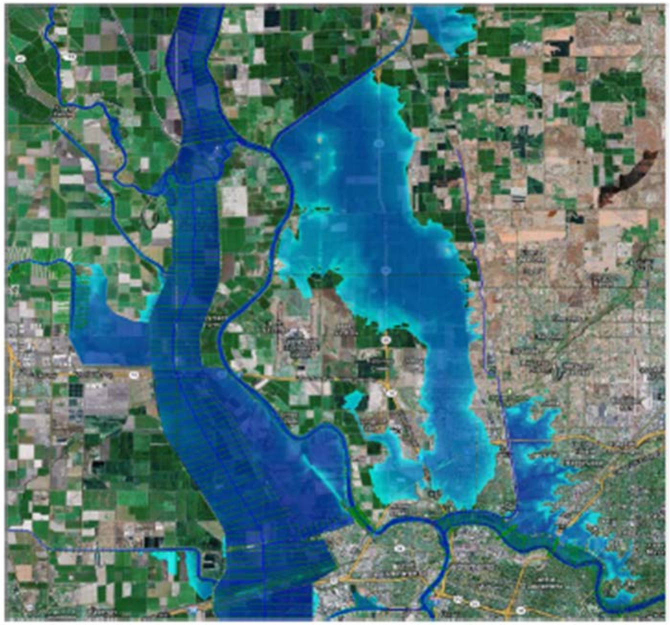
HEC-RAS is a computer program that models the hydraulics of water flow through natural rivers and other channels.

The US Army Corps of Engineer's Hydraulic Engineering Center (HEC) developed the River Analysis System (RAS) to aid hydraulic engineers in channel flow analysis and floodplain determination. It includes numerous data entry capabilities, hydraulic analysis components, data storage and management capabilities, and graphing and reporting capabilities. **RAS–Mapper is very impressive for GIS use.**

HEC-RAS v5.0.1 was used

http://www.hec.usace.army.mil/software/hec-ras/

HEC-RAS
River Analysis System



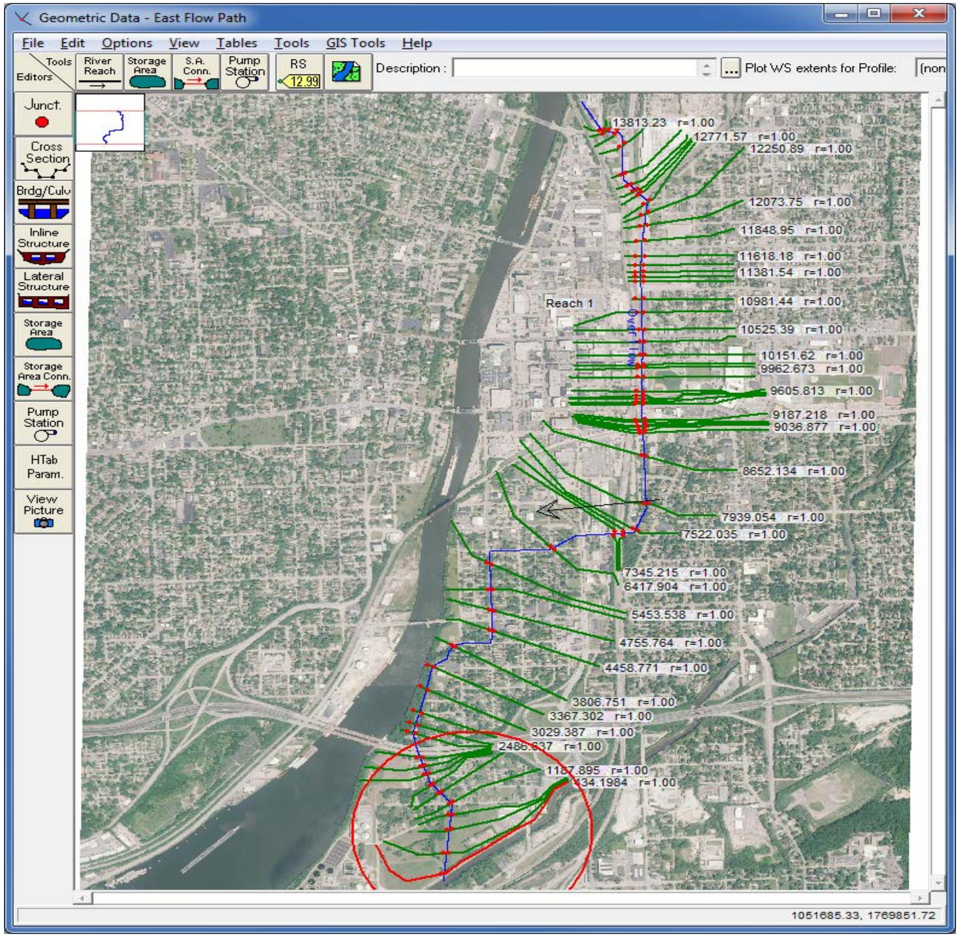
HEC-RAS River Analysis System, 2D Modeling User's Manual, Version 5.0, April 2015

US Army Corps
of Engineers
Hydrologic Engineering Center

1-D Model Limitations

For comparison purposes, a 1-D model was constructed along one of the main flow paths identified in the 2-D model. A street.

In the model, a stream CL and cross sections are entered essentially telling the model where water can and cannot flow. Limiting.



1-D Model Limitations – Cont'd

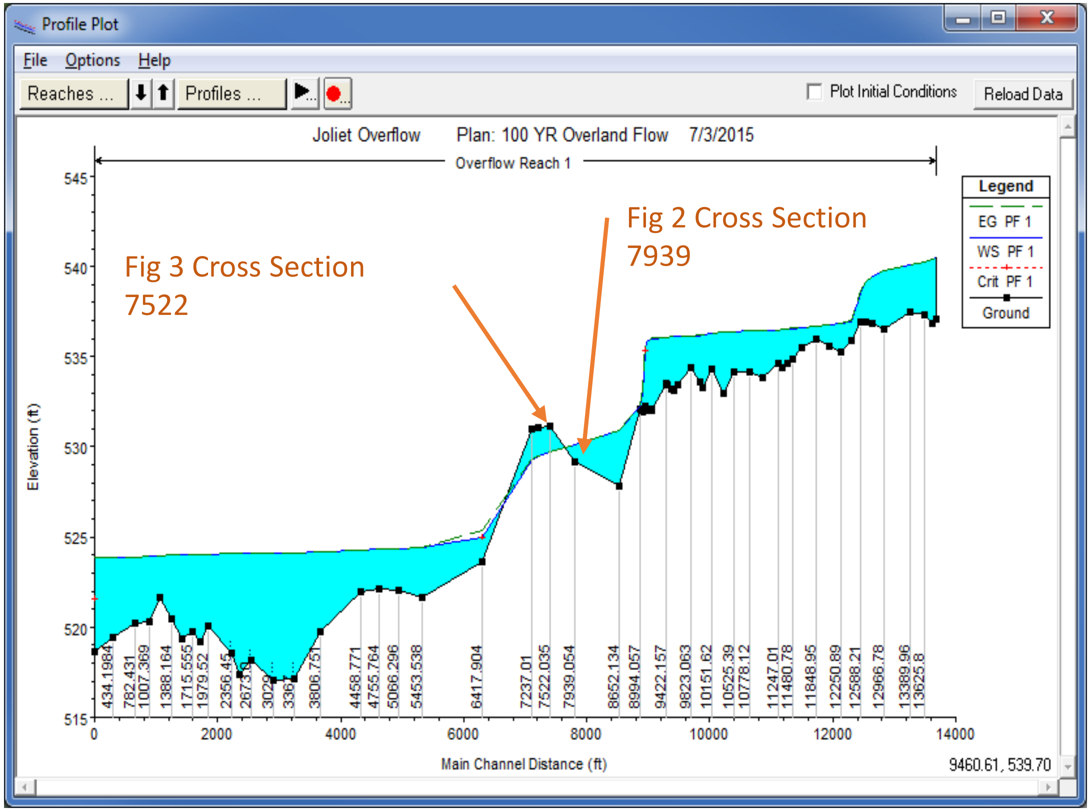


Figure 1

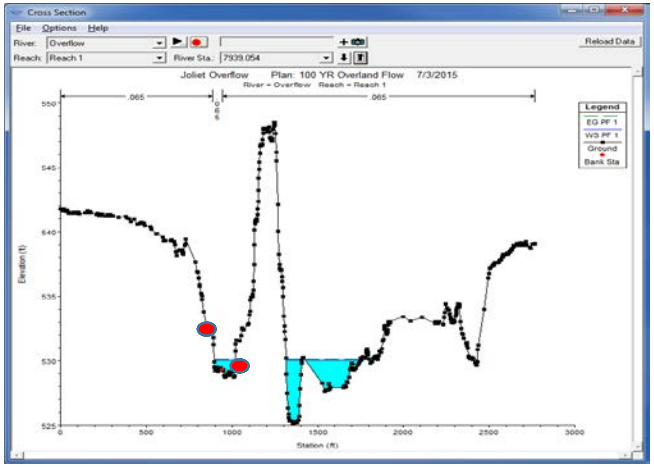


Figure 2. Cross Section 7939

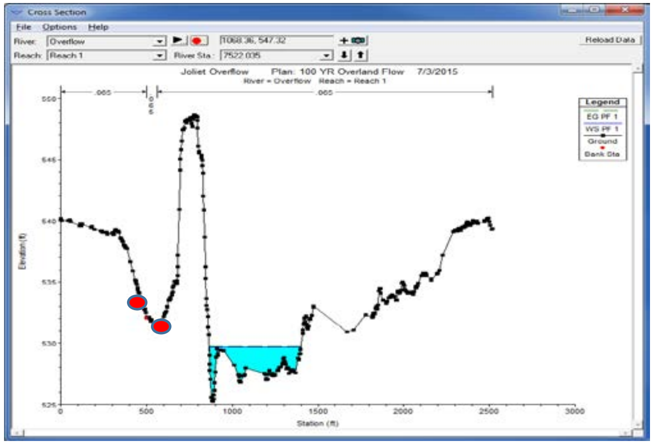


Figure 3. Cross Section 7522

ISWS 2D Model Inputs

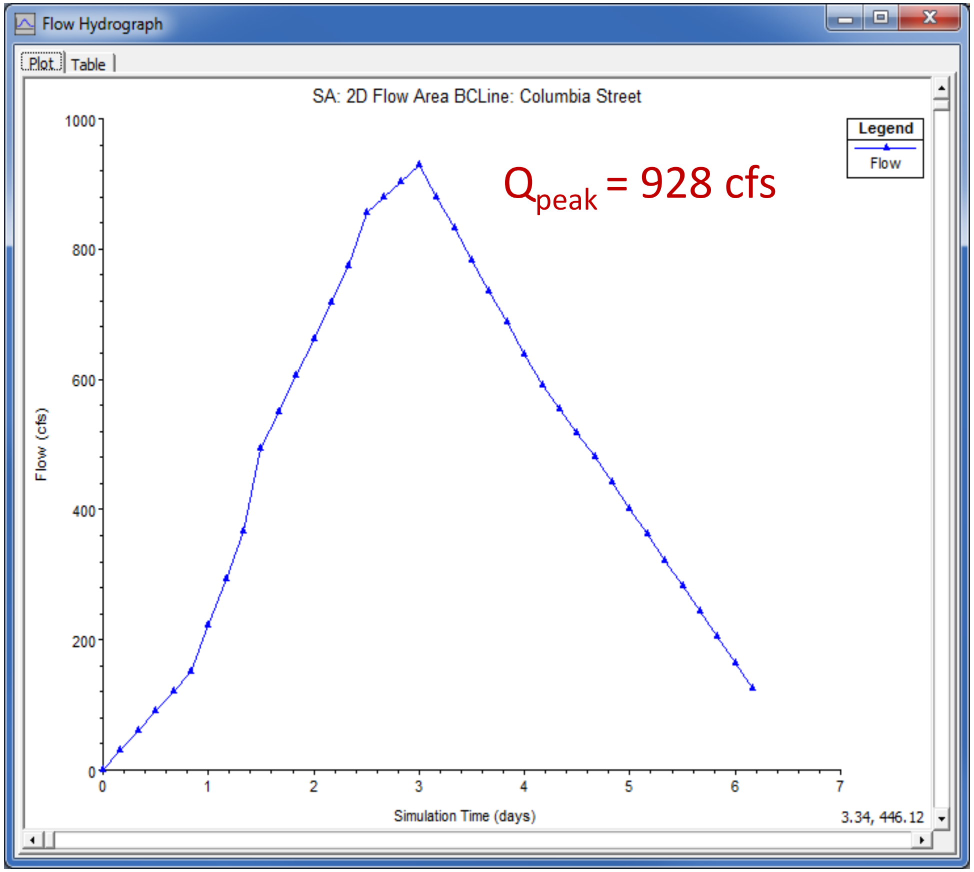
1. 2D Hydrograph Creation
2. Terrain
3. 2D Grid/Mesh
4. Manning's n-value

Hydrograph Creation

- A hydrograph was needed in order to determine if there would be enough volume of water to move thru the low-lying areas within the 2-D Flow Area and to its outlet.
- A steady-state model would flow to the outlet eventually, but an unsteady-state model, using a hydrograph based on a storm event, may or may not have enough volume to reach the outlet.

A 2-D *discharge* hydrograph was created by using the shape of the computed stage hydrograph from the 2004 UNET model and applying those stages to STARR's stage-discharge rating curves.

Peak discharge = 928 cfs.

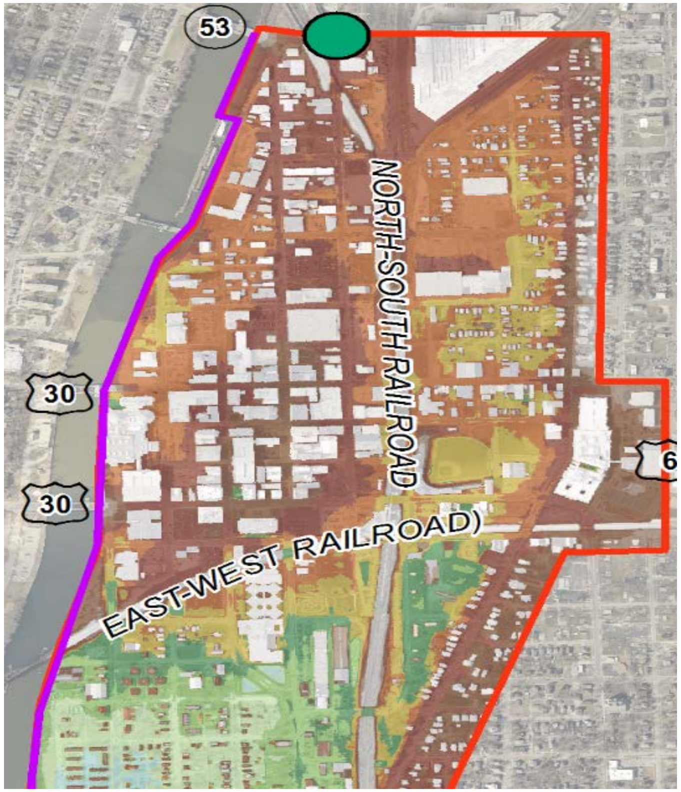


ISWS 2D Model Inputs

- 2D Hydrograph Creation
- Terrain
- 2D Grid/Mesh
- Manning’s n-value

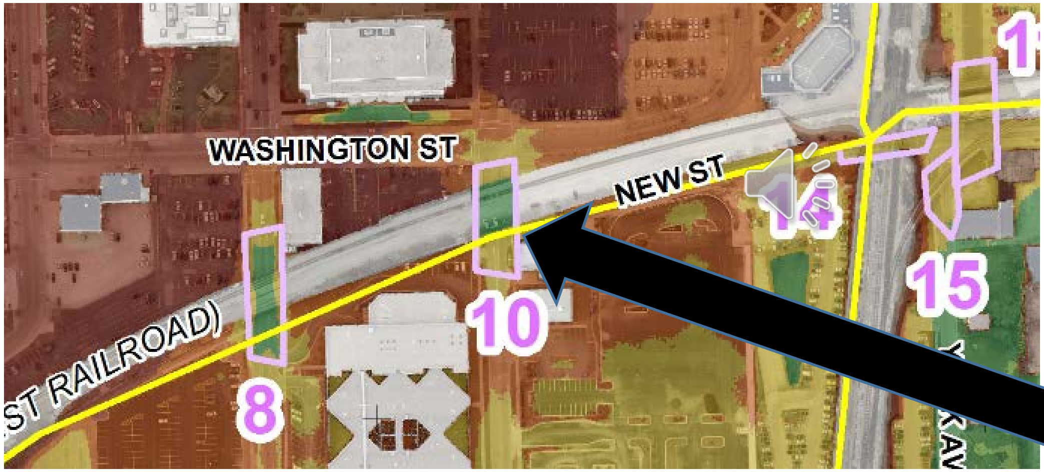
2014 Countywide LiDAR-Derived DSM

- HEC-RAS Terrain: Digital Surface Model (DSM)
  - Canopy/vegetation/trees were filtered out from LiDAR points.
  - Rooftops remained in the DSM, but had been removed in the DEM for floodplain mapping.



2014 CW LiDAR-Derived DSM

Developing a Terrain Model for use in 2D Modeling and Results Mapping/Visualization.



DSM was hydrologically corrected to consider cross-street openings.

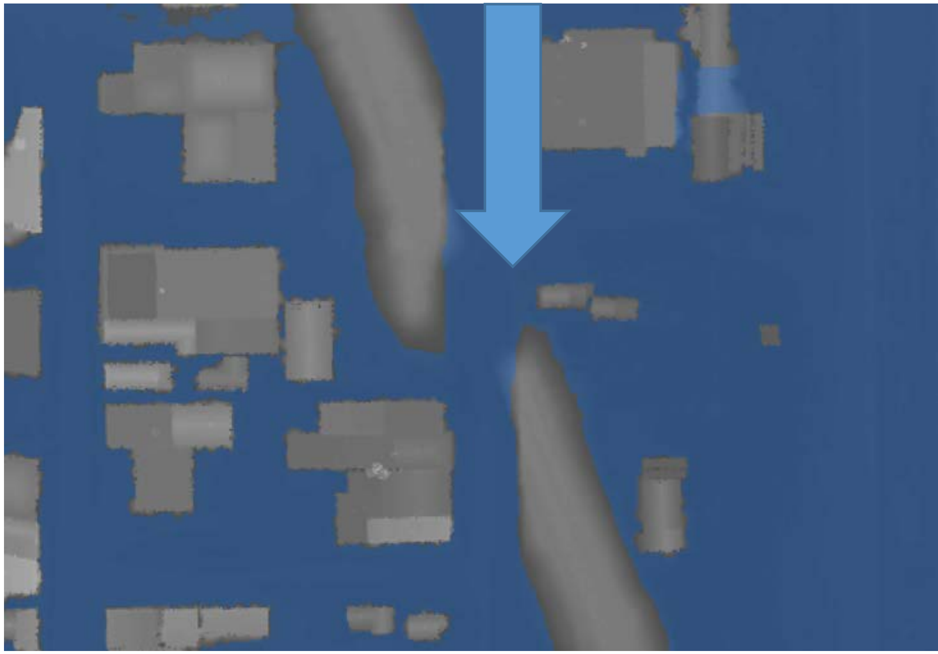
HEC-RAS Terrain: Digital Surface Model (DSM)

- Canopy/vegetation/trees were filtered out from LiDAR points.
- Rooftops (grey-colored structures) remained.

Opening under the Railroad Tracks

Floodplain Delineation Products:

- IF using a DTM (Digital Terrain Model)
  - Floodplain Delineation will see a smooth hydrologically corrected surface as if no buildings existed on the ground. Depth Grids will cover building footprint.
- IF using a DSM (Digital Surface Model)
  - Floodplain Delineation will be calculated seeing every building as high ground. Depth Grids will indicate a ZERO depth where buildings are shown on the DSM

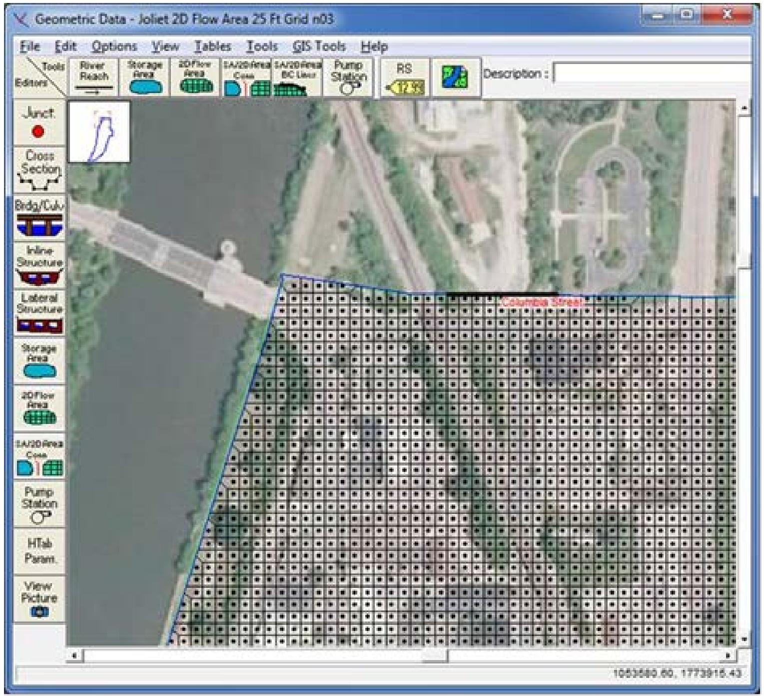


Slides prepared by Ryan Meekma (ISWS).

ISWS 2D Model Inputs

- 2D Hydrograph Creation
- Terrain
- 2D Grid/Mesh
- Manning's n-value

Development of a 2D Geometric Data Model



1. Draw a 2D flow area polygon;
2. Develop the 2D computational mesh (25 ft x 25 ft) for hydraulic computations;
3. Link the 2D flow areas to 1D model elements and/or directly connect boundary conditions to the 2D areas.
4. Approximately 40,000 cells.

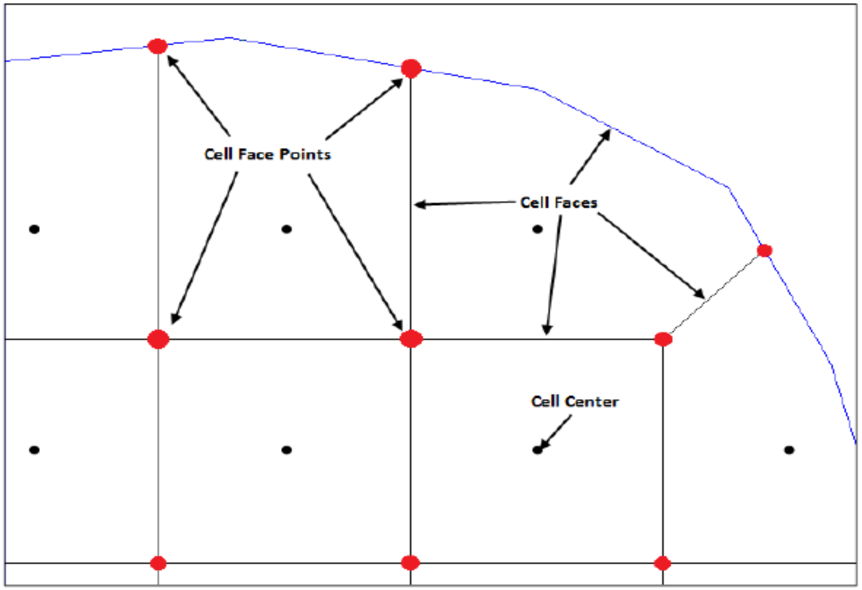
Some key factors for developing a good computational mesh with HEC-RAS are:

- Make sure the cell sizes, shapes, and orientations adequately describe the terrain.
- The cell size must be adequate to describe the water surface slope and changes in the water surface slope.

Potential Mesh Generation Problems - pan around for QA/QC

1. Cell has no cell center point
2. Cell face crosses over into multiple cells
3. Cell has more than one outer boundary face
4. Cell has too many faces (more than 8 sides)
5. Newest version has better tools for customizing the mesh/adding breaklines. Make sure cell doesn't straddle an embankment.
6. Hydraulic leaking

Cell Center:	The computational center of the cell. This is where the water surface elevation is computed for the cell.
Cell Faces:	These are the cell boundary faces. Faces are generally straight lines, except along the outer boundary of the 2D Flow Area, in which case a cell face can be a multi-point line.
Cell Face Points:	The cell Face Points (FP) are the ends of the cell faces. The Face Point (FP) numbers for the outer boundary of the 2D Flow Area are used to hook the 2D Flow Area to a Lateral Structure.



HEC manual, *Combined 1D and 2D Modeling with HEC-RAS (Brunner, 2014)*

ISWS 2D Model Inputs

- 2D Hydrograph Creation
- Terrain
- 2D Grid/Mesh
- Manning’s n-value

Manning’s n-value:

- N = 0.04
- Limited references on Manning’s.
- FLO-2D Reference Manual

Table 1. Overland Flow Manning's n Roughness Values[1]

Surface	n-value
Dense turf	0.17 - 0.80
Bermuda and dense grass, dense vegetation	0.17 - 0.48
Shrubs and forest litter, pasture	0.30 - 0.40
Average grass cover	0.20 - 0.40
Poor grass cover on rough surface	0.20 - 0.30
Short prairie grass	0.10 - 0.20
Sparse vegetation	0.05 - 0.13
Sparse rangeland with debris	
0% cover	0.09 - 0.34
20 % cover	0.05 - 0.25
Plowed or tilled fields	
Fallow - no residue	0.008 - 0.012
Conventional tillage	0.06 - 0.22
Chisel plow	0.06 - 0.16
Fall disking	0.30 - 0.50
No till - no residue	0.04 - 0.10
No till (20 - 40% residue cover)	0.07 - 0.17
No till (60 - 100% residue cover)	0.17 - 0.47
Open ground with debris	0.10 - 0.20
Shallow glow on asphalt or concrete (0.25" to 1.0")	0.10 - 0.15
Fallow fields	0.08 - 0.12
Open ground, no debris	0.04 - 0.10
Asphalt or concrete	0.02 - 0.05

[1]Adapted from COE, HEC-1 Manual, 1990 and the COE, Technical Engineering and Design Guide, No. 19, 1997 with modifications.

THEORY

2-D Equations

2-D St. Venant Equations

(Horizontal distance in X-direction)

$$\frac{\partial u}{\partial t} + u\left(\frac{\partial u}{\partial x}\right) + v\left(\frac{\partial u}{\partial y}\right) = -g\left(\frac{\partial H}{\partial x}\right) + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + f v \qquad (Eq. 2A, x)$$

(Horizontal distance in Y-direction)

$$\frac{\partial v}{\partial t} + u\left(\frac{\partial v}{\partial x}\right) + v\left(\frac{\partial v}{\partial y}\right) = -g\left(\frac{\partial H}{\partial x}\right) + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v - f u \qquad (Eq. 2A, y)$$

Where:

$\frac{\partial u}{\partial t}$ = Local Acceleration Term;

$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}$ = Advective Acceleration Term;

$g\frac{\partial H}{\partial x} = Hydrostatic\ Pressure\ Gradient\ Term;$

$v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) = Viscosity\ (Turbulence) Term;$

$c_f u = Bed\ Friction\ Term;$

$f v = Coriolis\ Parameter\ Term;$

2-D Diffusion Wave Equations

The 2-D Diffusion Wave Equations are based on the 2-D Full Momentum Equations with the Viscosity, Coriolis Parameter, Advective Acceleration, and Local Acceleration terms removed as shown below.

(Horizontal distance in X-direction)

$$\cancel{\frac{\partial u}{\partial t}} \cancel{+ u\left(\frac{\partial u}{\partial x}\right)} \cancel{+ v\left(\frac{\partial u}{\partial y}\right)} = -g\left(\frac{\partial H}{\partial x}\right) + \cancel{v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)} - c_f u + \cancel{f v}$$

(Horizontal distance in Y-direction)

$$\cancel{\frac{\partial v}{\partial t}} \cancel{+ u\left(\frac{\partial v}{\partial x}\right)} \cancel{+ v\left(\frac{\partial v}{\partial y}\right)} = -g\left(\frac{\partial H}{\partial x}\right) + \cancel{v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)} - c_f v - \cancel{f u}$$

Computational Time Step

1. The computational time step is a function of cell size and velocity of the flow moving through those cells. The computation time step, Δt, for the model runs was 1 second. The computational time step for each equation set can be calculated as shown in the figure.

2. Note that V is not the average velocity, but rather:
   a) V = stream velocity + wave celerity

3. The idea is that a particle of water enters a grid cell and should not travel through it until a computation step has been completed. We used a 25 ft x 25 ft grid. If we say our velocity could be 5 feet/sec, the time across the grid would be = 25 feet/5 feet sec = 5 sec. Therefore, we want to choose a time step less than 5 sec to ensure the particle did not leave the cell too soon. We chose 1 sec time step, which is well below the Courant number of 1.0 for using the Full Saint Venant Equations (this is shown below).
   a) (5 feet/sec x 1 sec)/(25 feet) = 0.2 which is less than 1.0.

Full Saint Venant Equations:

$$C = \frac{V * \Delta T}{\Delta X} \leq 1.0 \quad (with\ a\ \max\ C = 3.0)$$

Where:	C	=	Courant Number
	V	=	Velocity of the Flood Wave (ft/s)
	ΔT	=	Computational Time Step (seconds)
	ΔX	=	The average Cell size (ft)

Diffusion Wave Equations:

$$C = \frac{V * \Delta T}{\Delta X} \leq 2.0 \quad (with\ a\ \max\ C = 5.0)$$

(Taken from page 89 of *Combined 1D and 2D Modeling with HEC-RAS* by Gary Brunner, October 2014)

HEC-RAS 2-D Flow Modeling Capabilities

- 1D steady or unsteady flow modeling.
- Two-dimensional (2D) unsteady-flow modeling:
  - full Saint Venant equations (full momentum) or
  - Diffusion Wave equations)
- Combined 1D and 2D unsteady-flow routing.

In general, the 2D Diffusion Wave equations allow the software to run faster, and have greater stability properties. The 2D Saint-Venant equations are applicable to a wider range of problems.

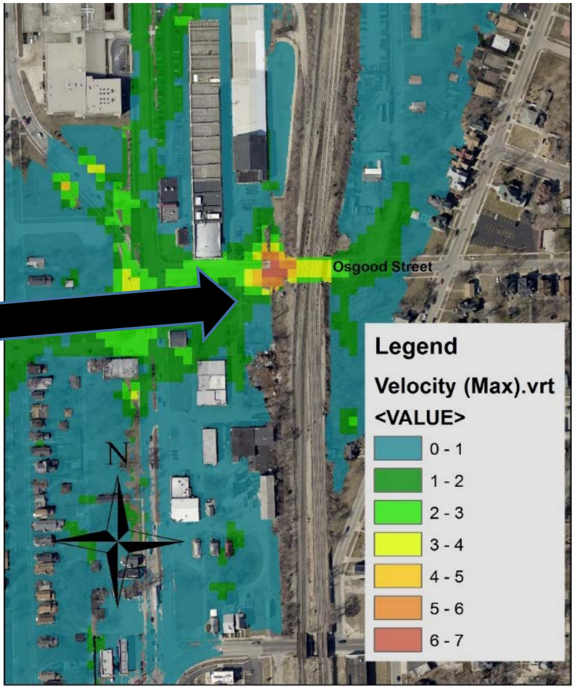
The project used the full 2D Saint Venant equations to capture the local accelerations between structures and openings.

RESULTS

Discussion of Results

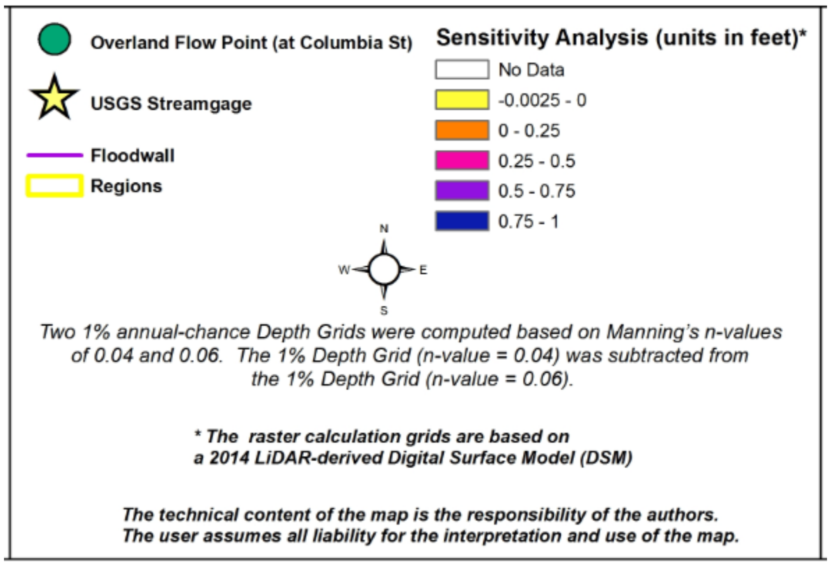
- Sensitivity Analysis (Manning's n-value and Equation Set)
- 4 Flow Paths and Flood Profiles:
  - They show flood depths up to 8 feet;
  - pass thru the major openings in the RR embankment and provide more accurate flood elevations than just reading BFEs from the FIRM.
- Higher velocities thru cross-street openings
- Model Run time:
  - Full Momentum = 14 hours
  - Diffusion Wave = 3 hours
- Overland flow travel time approximately 40 hours to Hickory Creek outlet.
- QAQC
  - Conservation of mass
- Calibration
  - Nothing to calibrate to - remember that our scenario has not occurred yet! Our scenario is not rainfall-based, but rather an example of hydraulic routing through the culverts based on the Des Plaines River stage and then thru the city as overland flow.
  - City says it has not experienced flooding in this area – no HW marks.
- 1D model comparison:
  - Similar flood depths but not appropriate to model multiple flow paths
- Mapping

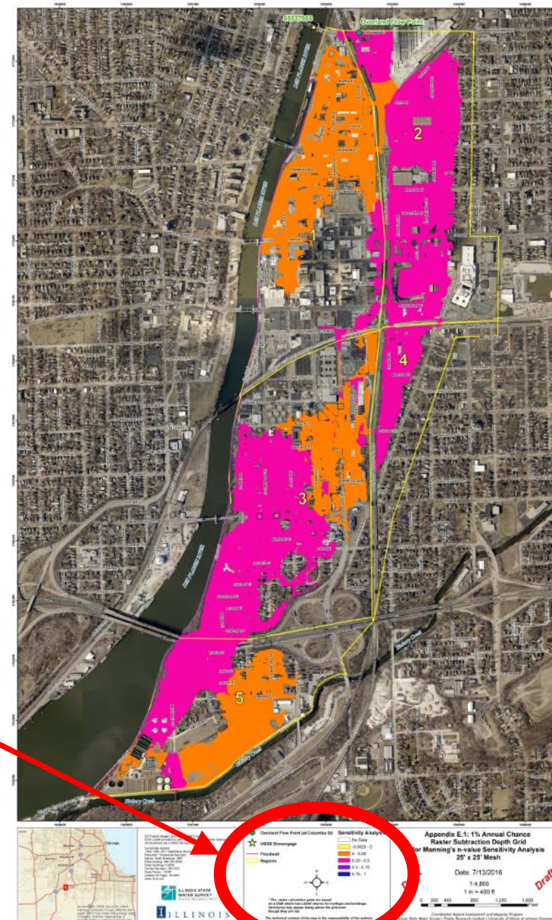
Velocity gradient at restriction



Sensitivity Analysis

Manning's n-

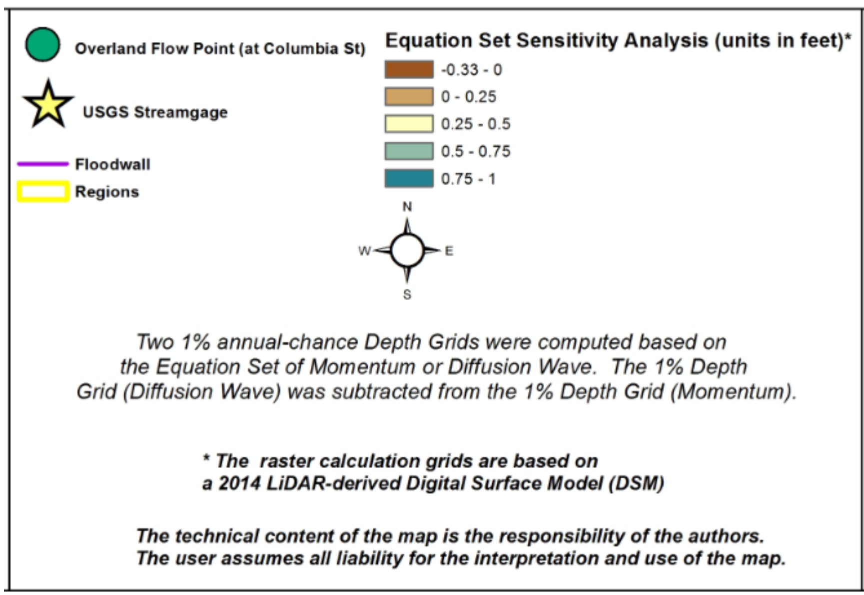


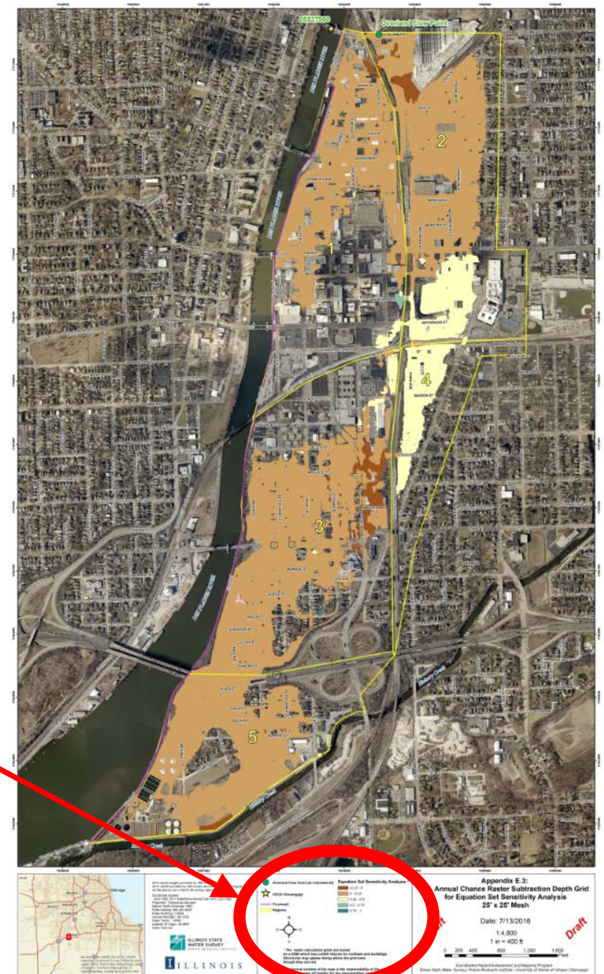


Sensitivity Analysis

Equation Set: (Full Momentum vs Diffusion Wave)

Difference typically ranged from 0 to 0.25 feet, but up to 0.5 feet.



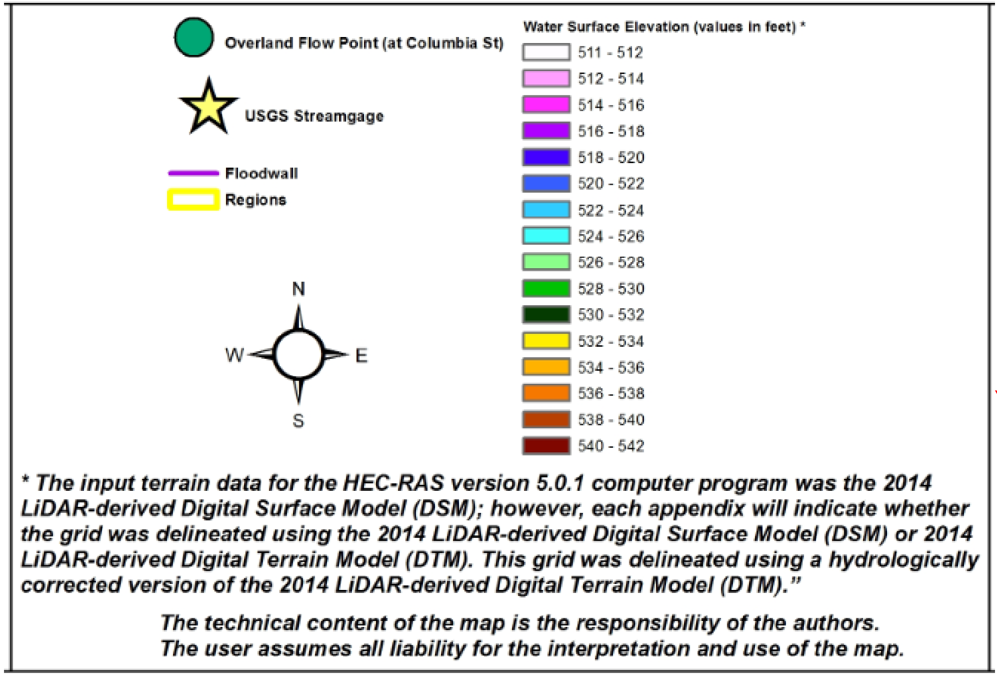


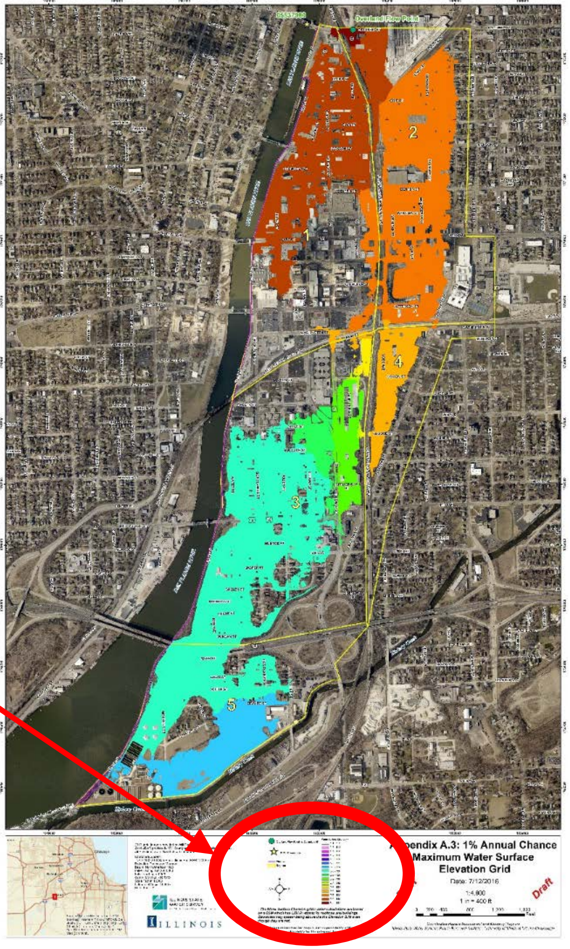
Sensitivity Analysis
Time Step (Δt)

Δt=1s, Computational error = None
Δt=2s, Computational error = 0.2 ft
Δt=3s, Computational error = 0.3 ft
Δt=5s, Computational error = 0.8 ft
Δt=10s, Computational error = 3 ft

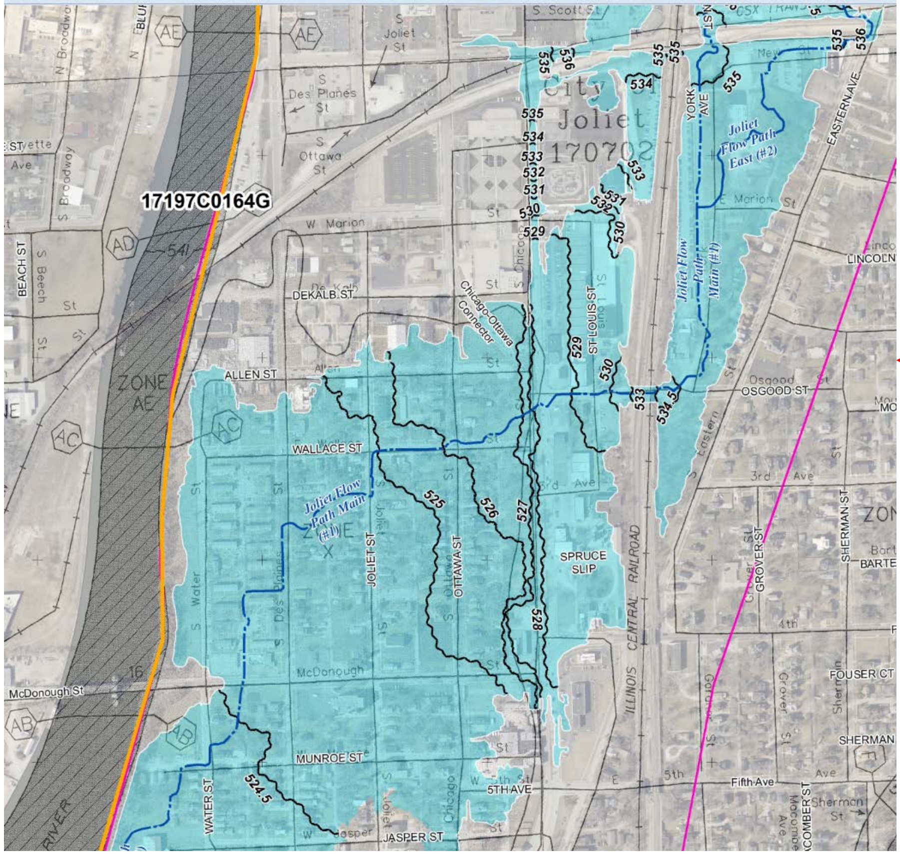
Max WSEL Grid Error = few tenths

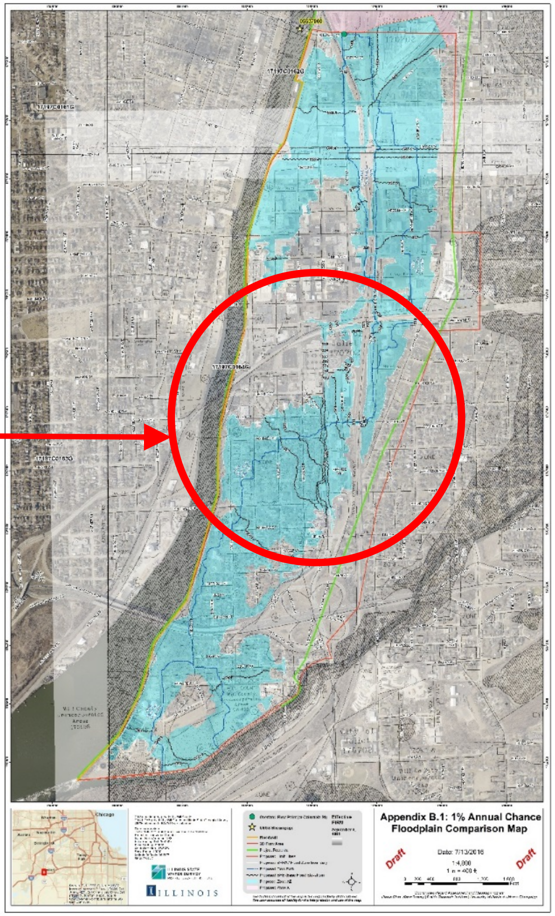
1% ACF Maximum WSEL Grid



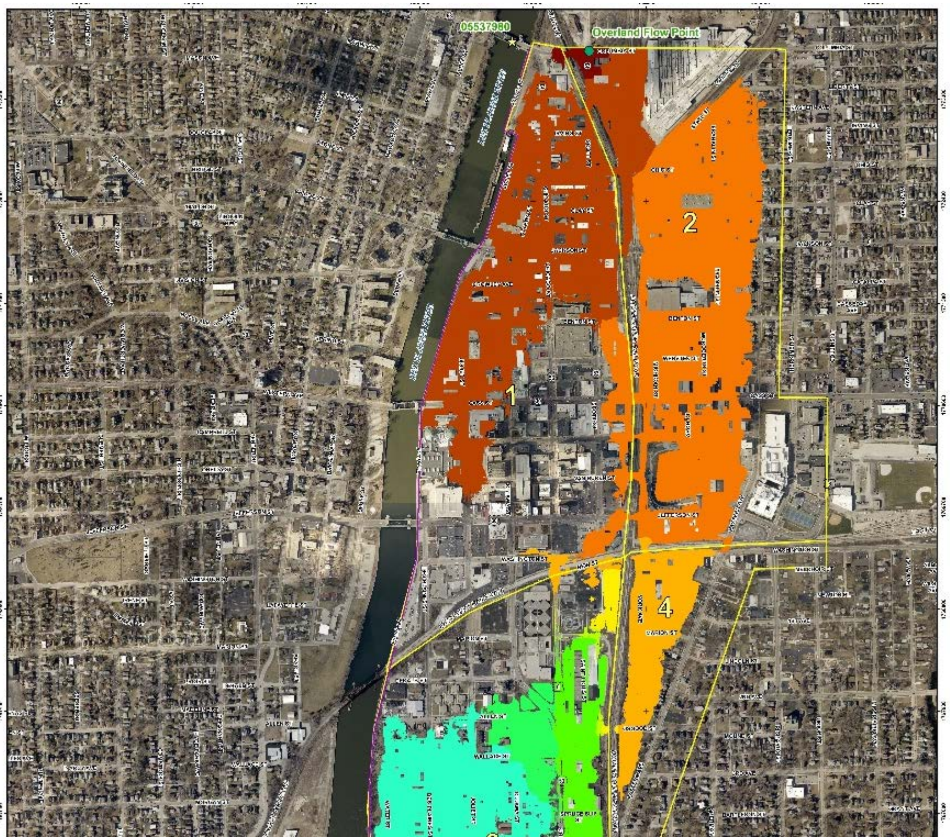


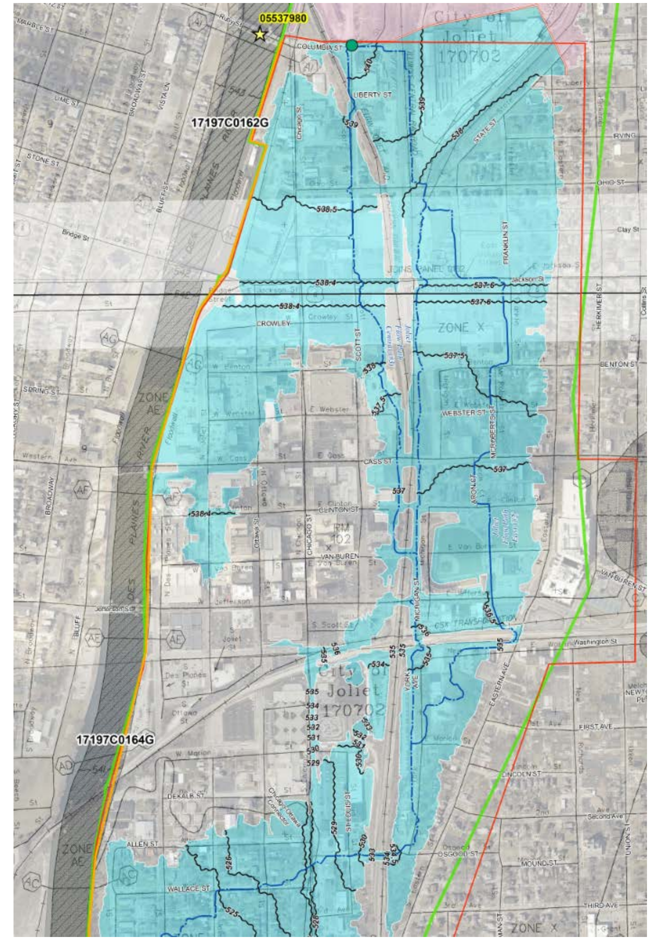
Proposed 1% ACF Floodplain



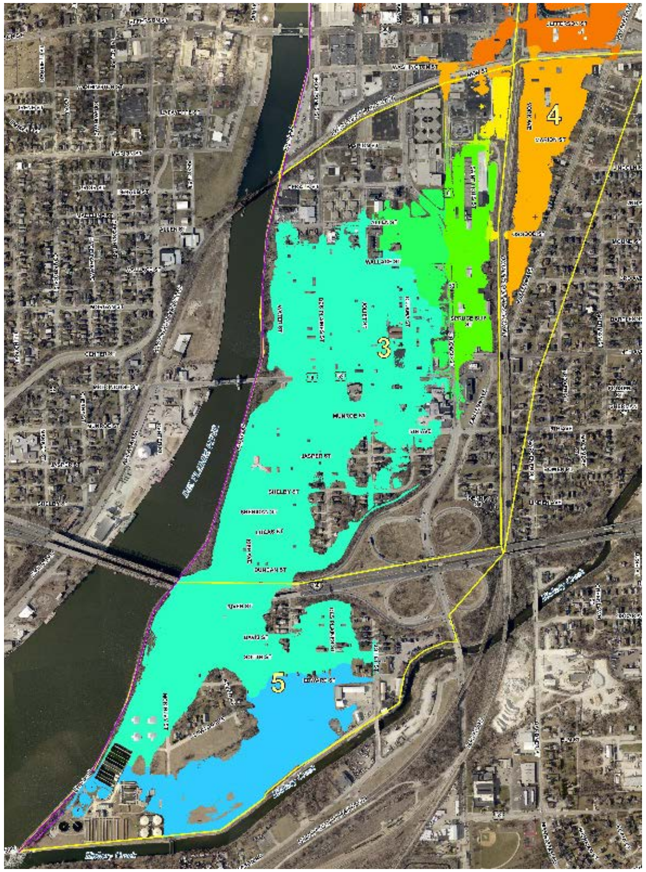


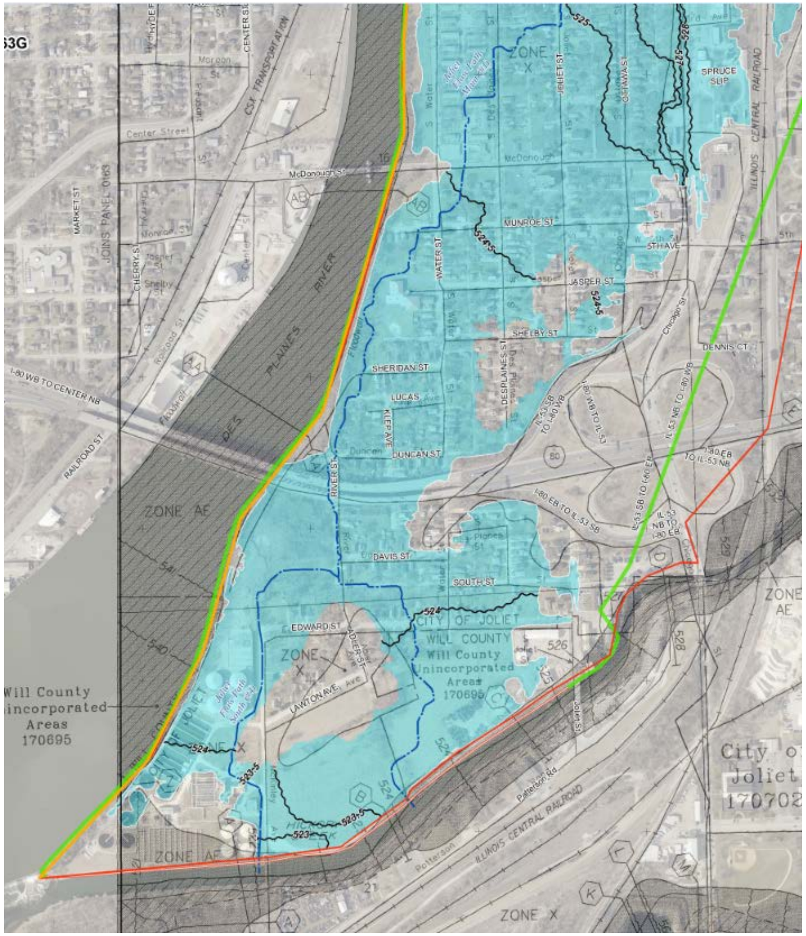
Proposed 1% ACF Floodplain



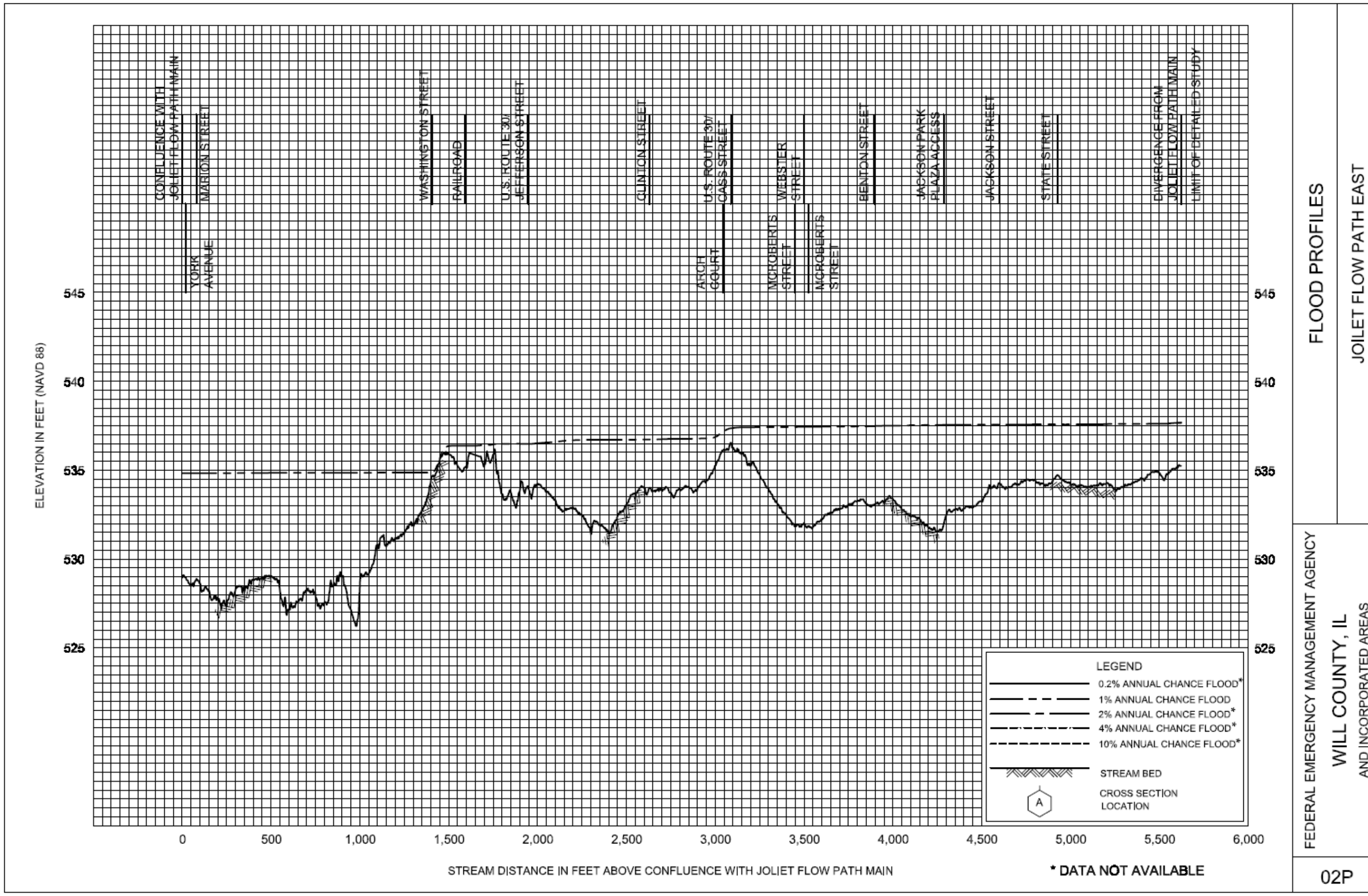


Proposed 1% ACF Floodplain





Proposed 1% ACF Profile



QA/QC & Calibration

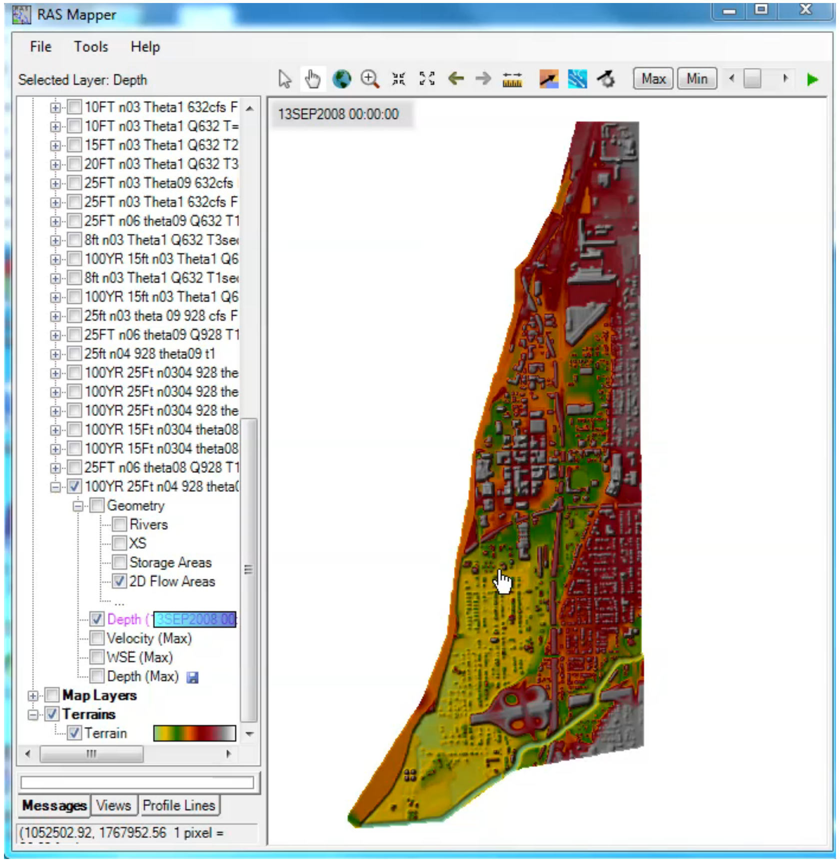
- QA/QC:
  - Performed a volume check
- No events to calibrate to because the City has not experienced an overflow scenario like this.

2D Modeling Assumptions

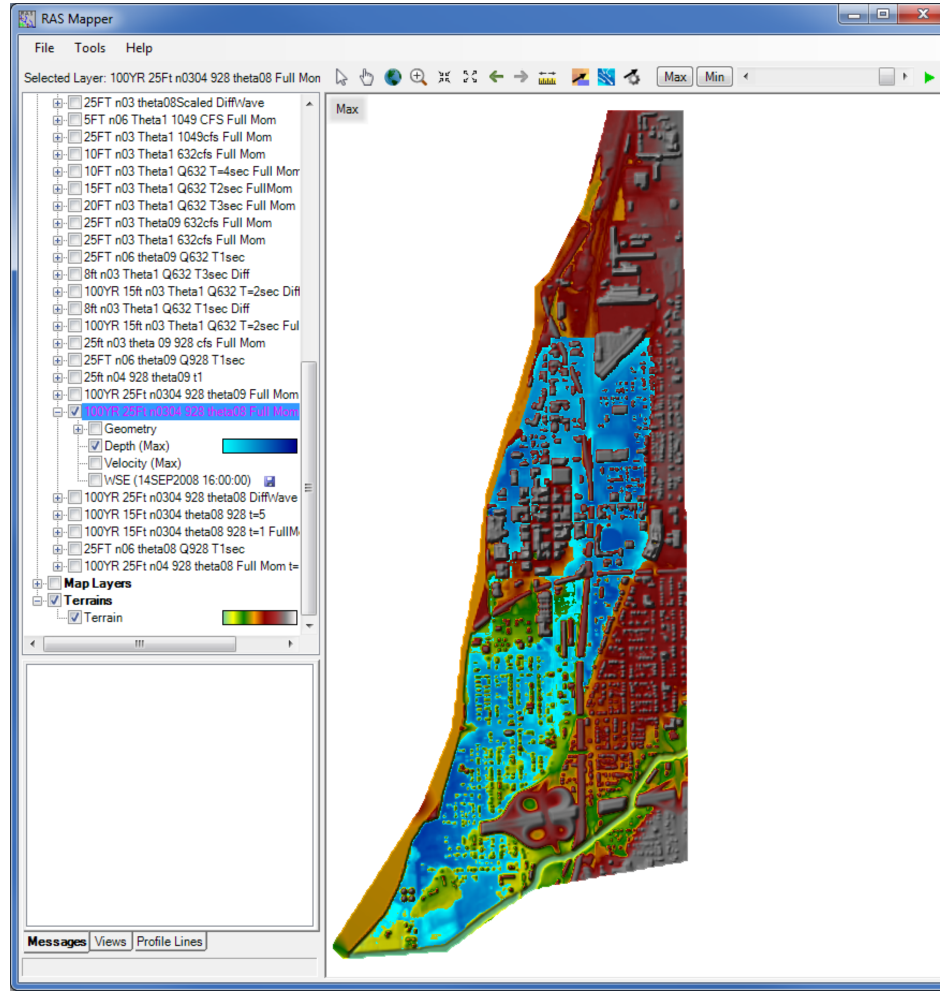
- Ignored local stormwater system (typically designed to capture the smaller, more frequent events)

RAS Mapper – 1% ACF Max Depth Grid Animation

- Click below the image to play animation. The animation shows the movement of flow throughout the 2D Flow area over time. At approximately time = 40 hours the flow reaches Hickory Creek at the southern boundary of the 2D Flow Area.

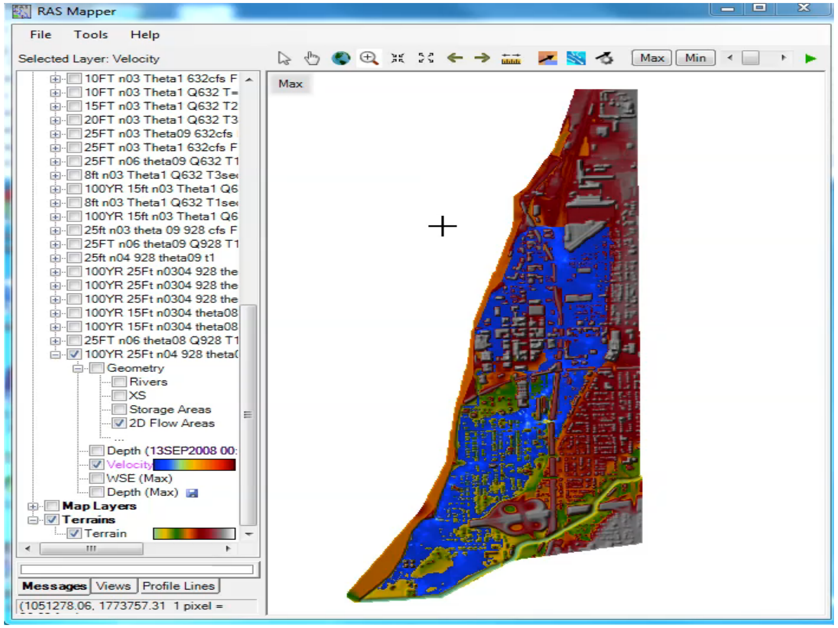


RAS Mapper – 1% Annual Chance Flood (ACF) Max Depth Grid



RAS Mapper – 1% ACF Max Velocity Grid Animation

Click below the image to play animation. The animation shows the movement of flow throughout the 2D Flow area using particle tracing. The heavier arrows indicate paths of more flow.



Summary

1. This is not a rainfall event within Joliet!
2. 2D results are being incorporated into the new FEMA FIRMs:
   - Structures Inundated (100 commercial, 12 industrial, 4 gov, 3 educ, 21 religious, 502 resident.
3. Outreach with the City:
   - Flood Risk Review Meeting was held with the City
4. Risk Assessment:
   - ISWS has completed a structure-based flood risk assessment using HAZUS to determine Average Annualized Losses (AAL).
   - The City is planning to perform a cost-benefit analysis to evaluate potential flood reduction improvements.
5. The City can better understand the magnitude of flooding at specific locations, and communicate flood risk to stakeholders. This was the main purpose of the study.

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